Rapid Processing Method for Large, Low-Expansion, Light-Weight Mirrors

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Applications Needs

- Applications in semiconductor capital equipment, thermal management, automotive, aerospace, defense and armor markets require
  - High Specific stiffness (stiffness/density : E/p)
  - High thermal stability (thermal conductivity/coefficient of thermal expansion: k/CTE)
  - Light weight and high hardness
  - Good strength and fracture toughness
  - Manufacturing techniques
    - Cost effective
    - Large scale
    - Complex shape capability

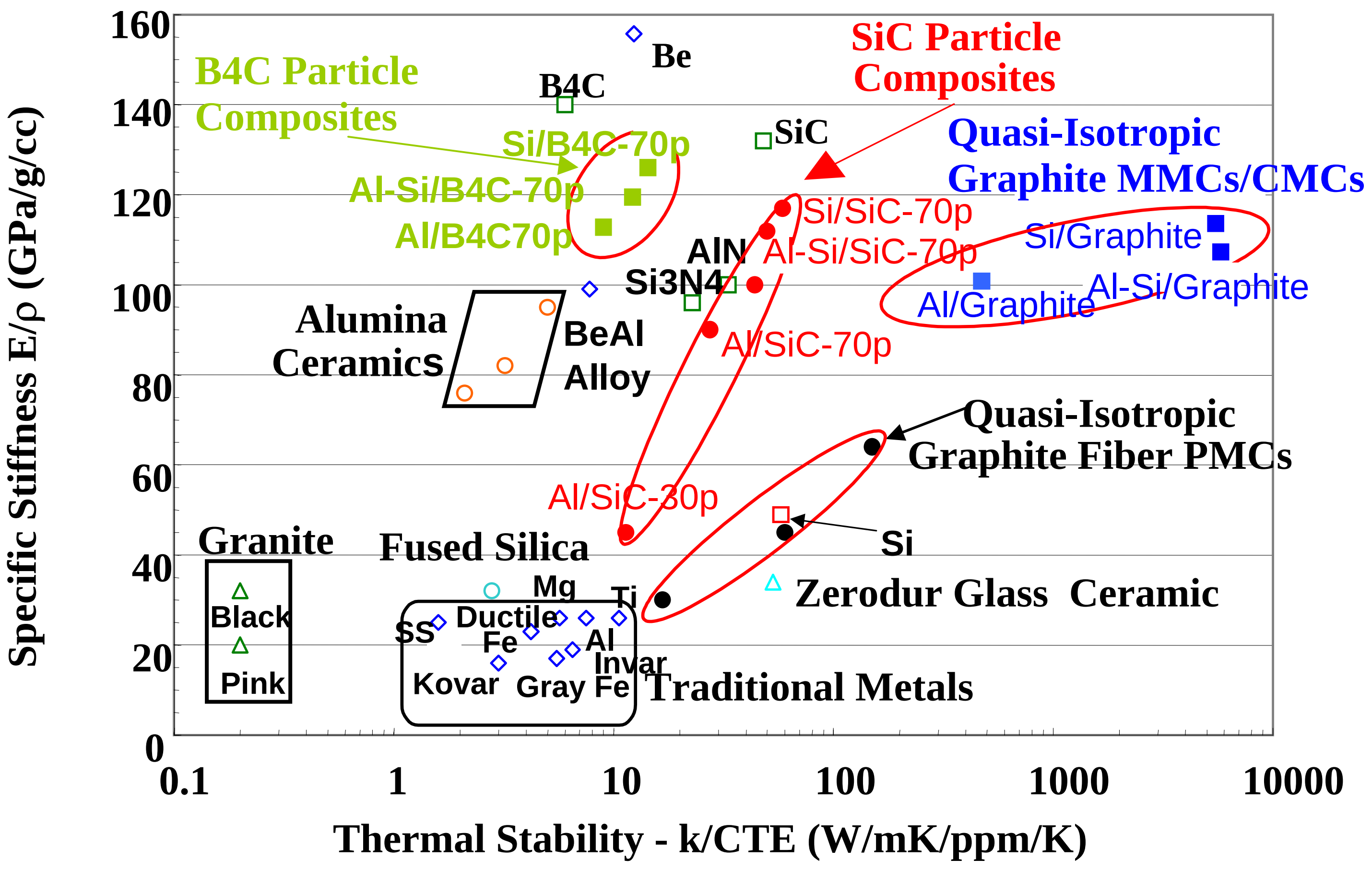
Mirror Applications: Requirements

	ρ Density g/cc	α CTE ppm/K	k Thermal Conductivity w/mK	E modulus (GPa)	E/ ρ	k/ α	Specific Heat J/kg K	Polish-ability
Desired →	***Low***	***Low***	***High***	***High***	***High***	***High***	***High***	***Fast***
Al	2.7	27	237	126	47	8.8	899	
Be	1.85	11.4	150	300	162	13.1	1820	slow
Si	2.33	2.6	150	47	20	58	710	fast
C/SiC(IABG)	2.7	2	125	250	93	63	700	slow
Duocel SiC	3.22	4.5	--	414	129		--	
CVD SiC	2.95	2.4	175	364	123	73	700	slow
Reaction bonded SiC#	2.95	2.44	156	315	107	64	670	slow
Silica	2.2	0.65	--	70	32		708	fast
ULE	2.2	0.03	1.3	73	33	43	--	fast
Zerodur	2.55	0.05	1.64	80	36	39	820	fast
Gr/epoxy	1.49	0.45	--	270	174	--	--	
Gr/ester	1.53	-1	--	558	365	--	--	
M Cubed Reaction Bonded Materials								
Si/SiC(70%)	2.95	2.9	170	350	119	59	680	Fast
Si/SiC(80%)	3.03	2.9	185	380	125	64	670	Fast
Si/B_4C(70%)	2.57	4	100	382	149	25	890	Fast
C_f/SiC	**2.4**	**-0.5 to 0.5**	**100-200****	**100-250****	**40-100****	**>150****	**--**	**Fast***

** - Tailorable by choosing fiber and interface

Based on a table in ref. P. S. Carlin, "Light weight mirror systems for spacecraft- An overview of materials and manufacturing needs," Proceedings of IEEE Aerospace conference, 18-25 March, 2000, Big Sky Montana, Vol. 4, pg. 169-182.

Specific Stiffness Vs Thermal Stability



Metal/Ceramic Composites Offer Excellent Properties

- **Reaction Bonded SiC**
  - **SSC-702 (70% SiC, 30% Si)**
  - **SSC-802 (80% SiC, 20% Si)**
- **Reaction Bonded B_4C**
  - **RBBC-751 (75% B_4C, 9% SiC, 16% Si)**
- **Reaction Bonded Hybrid Composites**
  - **HSC-701 (70%SiC, 18%Al, 12%Si)**
  - **HSC-702 (70%SiC, 12%Al, 18%Si)**
  - **HSC-703 (70%SiC, 7%Al, 23%Si)**
- **Reaction bonded C_f/SiC under development with near-zero CTE**
- **Metal Matrix Composites (MMC) – PRIMEX Process**
  - **ASC-301 (30%SiC, 70% Al) - Cast**
  - **ASC-401 (40%SiC, 60% Al) - Cast**
  - **ASC701 (70%SiC, 30% Al) - Infiltrated**

Advantages of MCT's Reaction Bonding Technology for Processing SiC and B_4C-Based Materials

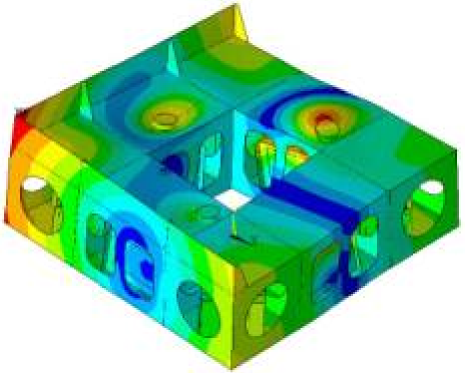
Process	Shape & Size Capability	Process Temp. Reactivity	Process Time	Tooling cost	Residual Porosity	Scalability	Cost
CVD	Limited	Low	Long	High	Low	Poor	High
CVI	Limited	Low	Long	High	High	Poor	High
Hot Pressing	Limited	High	Short	High	Low	Poor	High
Sintering	Good	High	Medium	High	Low	Medium	Medium
MCT Reaction Bonding	Excellent	Low	Short	Low	Low	Excellent	Low

Reaction Bonding

- **Process used since 1940s: AKA: reaction sintering, self bonding, melt infiltration**
- **Makes use of good wetting and highly exothermic reaction between carbon and liquid Si or Si-alloy**
- **M Cubed refined this process to achieve**
  - **Fine microstructure**
  - **Higher toughness**
  - **Near-net shape preforming technique that yields high SiC content (>70%)**
  - **Environmentally friendly**
  - **Better machinability (EDM)**
  - **Very low shrinkage(< 0.5%) from preform to infiltrated product**
  - **High strength preforms allow “green” machining to high tolerances which minimizes finish machining**
  - **Preform bonding technology allows manufacturing of complex parts**
  - **Cost-effective, large-scale manufacturing and manufacturing of large, complex components**

Reaction Bonding Process Steps

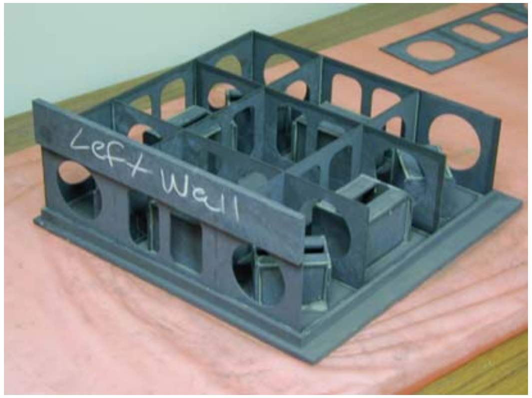
- Design and Analysis
- Mold Fabrication
- Preform Fabrication
- Green Machining
- Preform Bonding
- Infiltration



Design/Analysis

Preform Fabrication

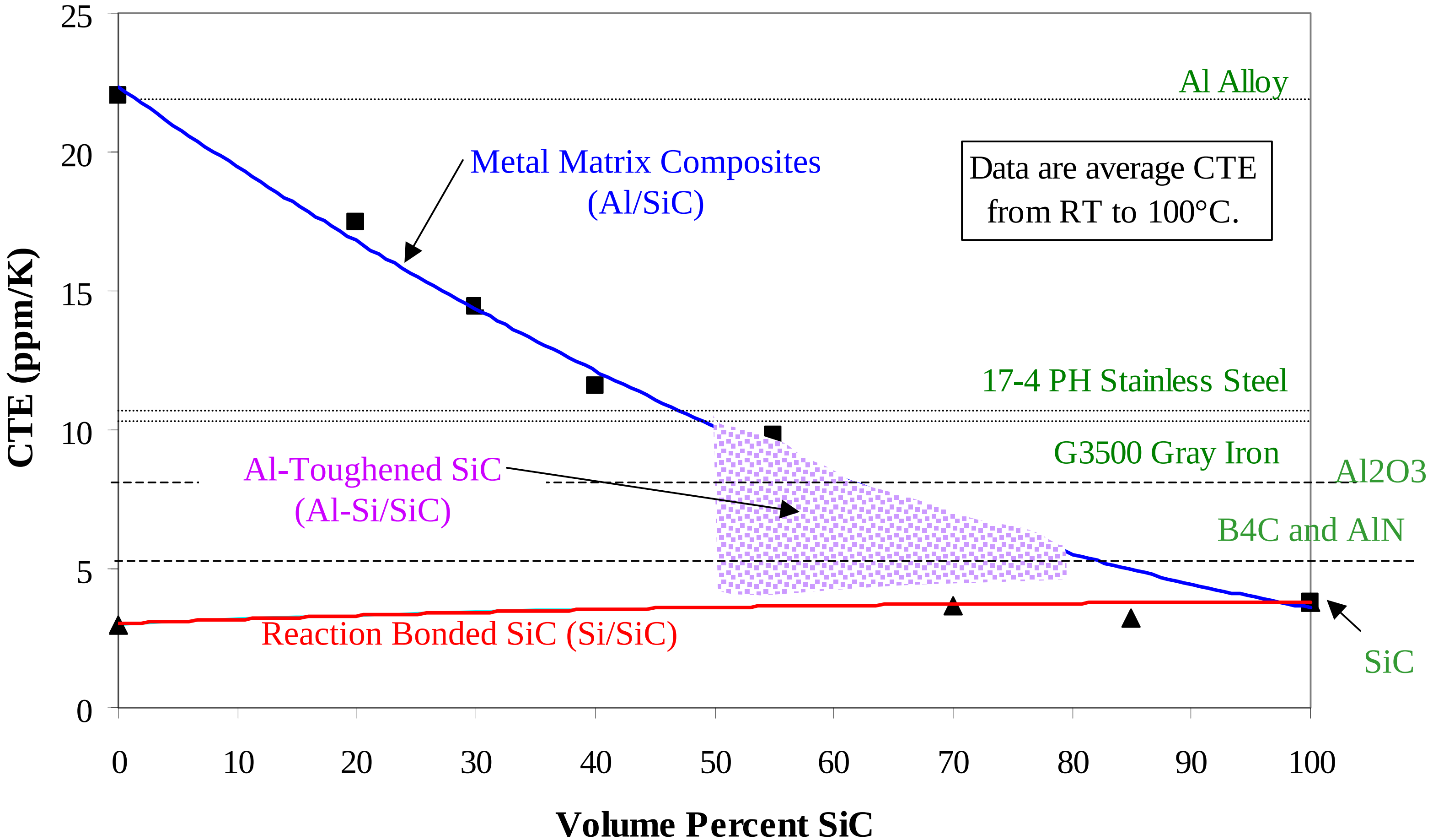
Green Machining



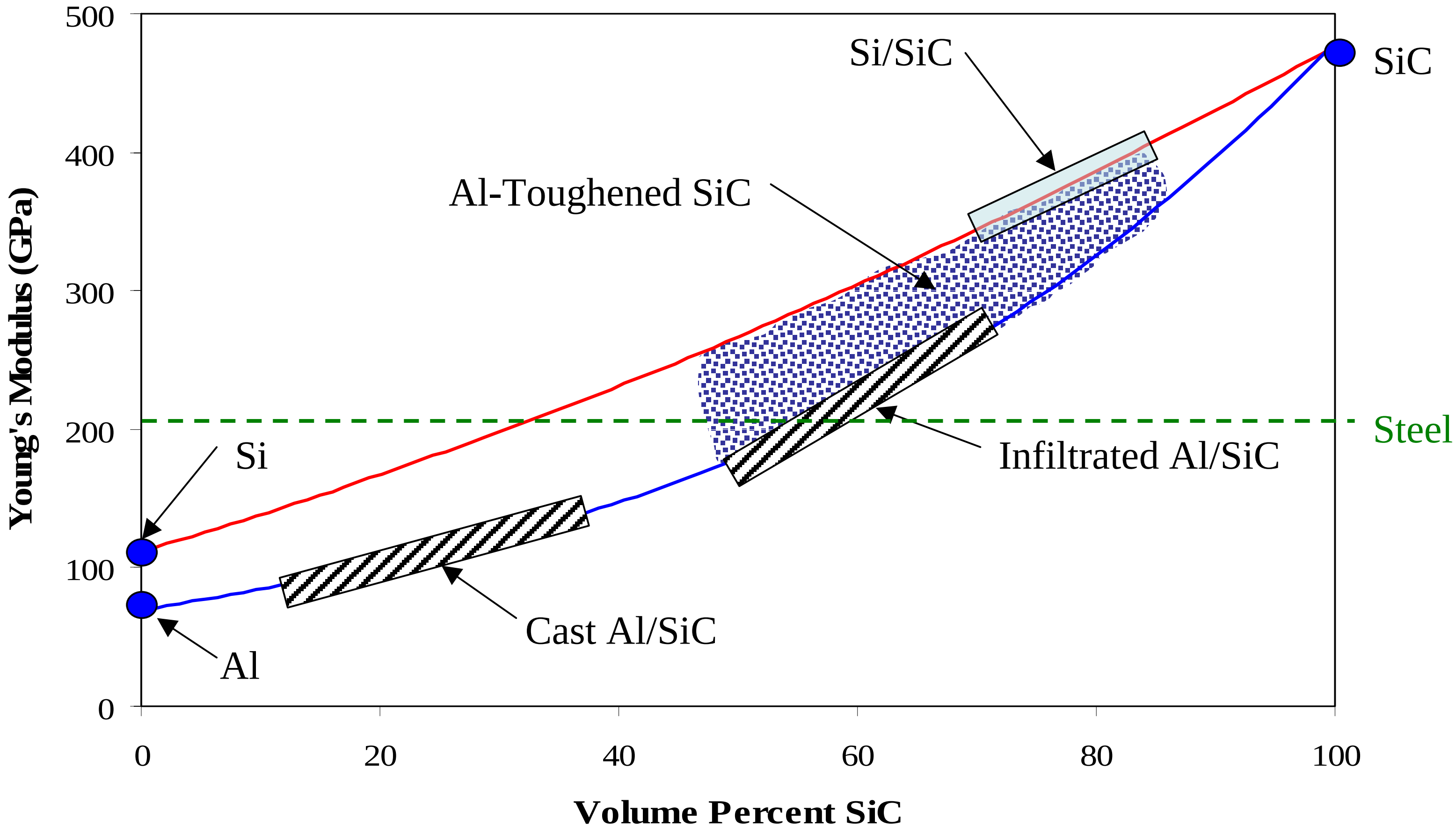
Preform Assembly/Bonding

Infiltrated Structure

CTE Comparison of M Cubed SiC-Reinforced Composites

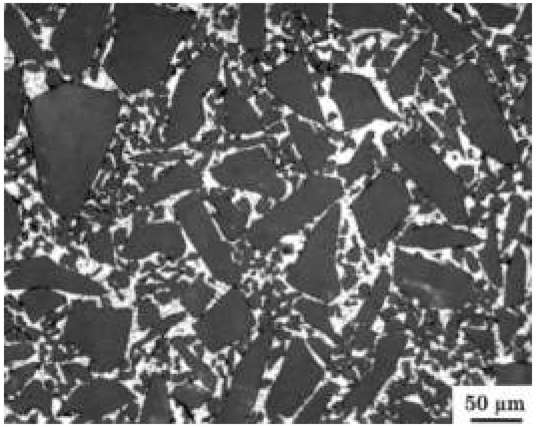


Stiffness Comparison of M Cubed SiC-Reinforced Composites

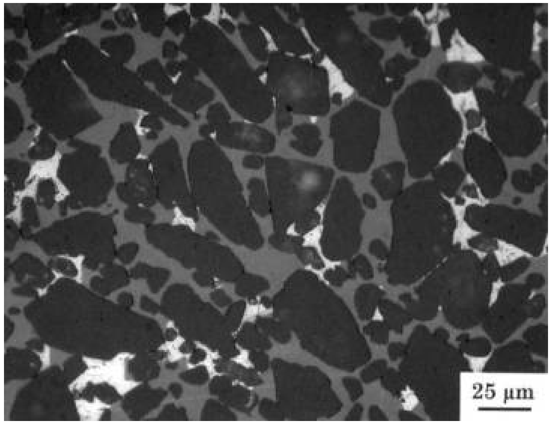


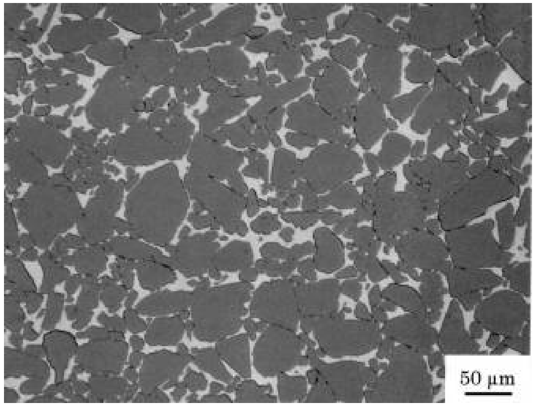
Composite Microstructures

Al/SiC-70p

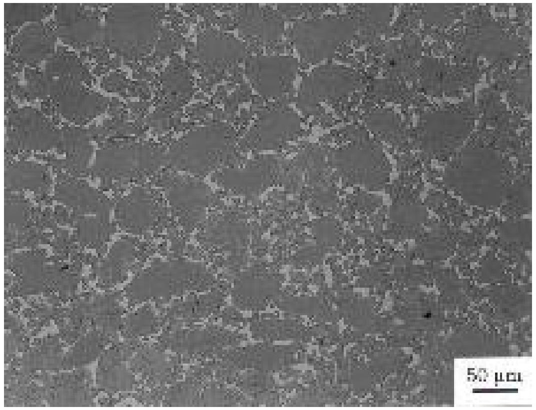


Al-Si/SiC-70p





Si/SiC-70p



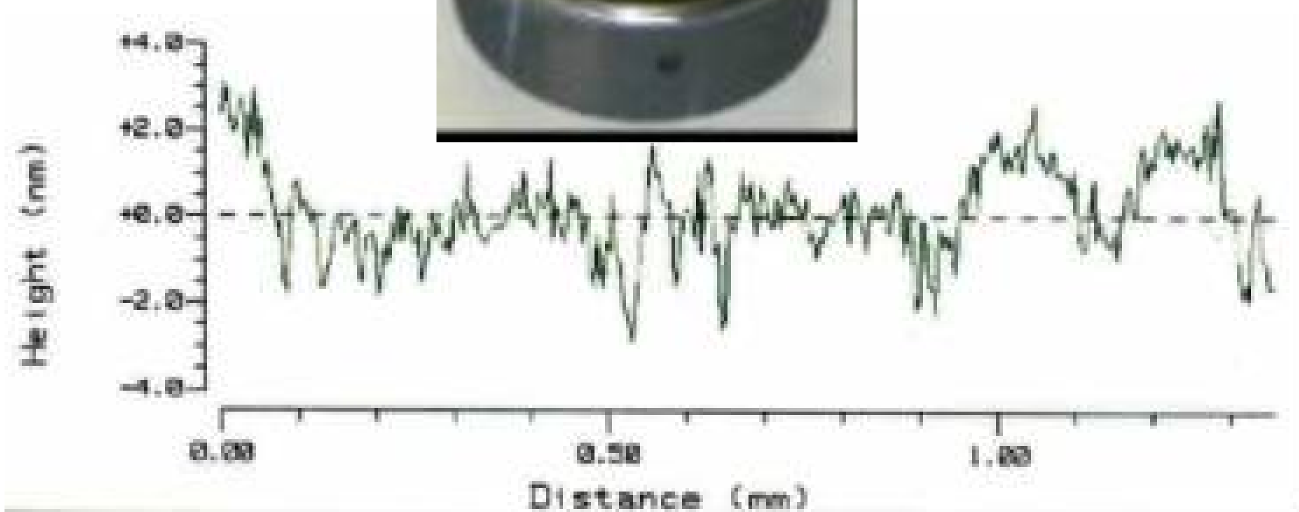
Si/B_4C-70p

Large-scale Manufacturing

- Reaction bonding process was scaled up to produce ceramic tiles for small arms protective insert (SAPI) personnel armor
- Current capacity 15,000/month
- Robust process was first developed using Kaizen principles
- Statistical process control tools employed for process control
- Thorough inspection is performed on samples from each lot

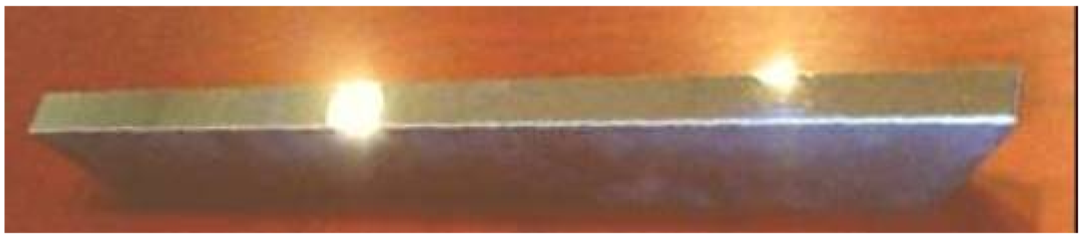
RB SiC: Mirror Substrate Test Coupon

RMS roughness 1 nm

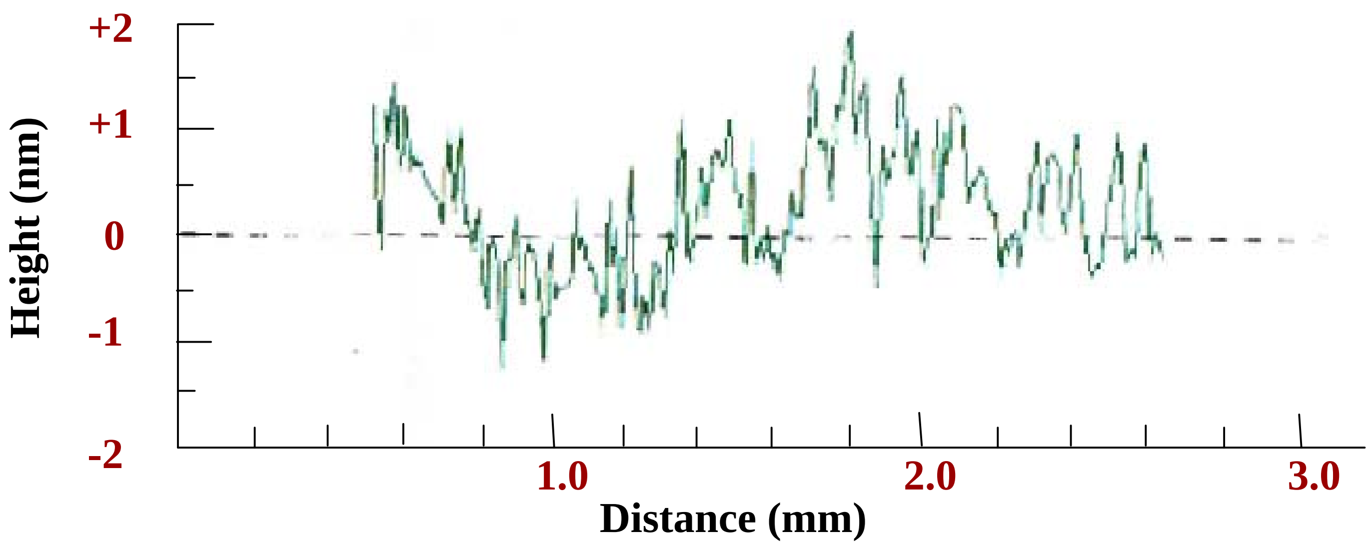


Example of MCT RB SiC Precision Mirror

Strip Mirror



Roughness Plot



Light Weight Si/SiC Substrates for Mirrors

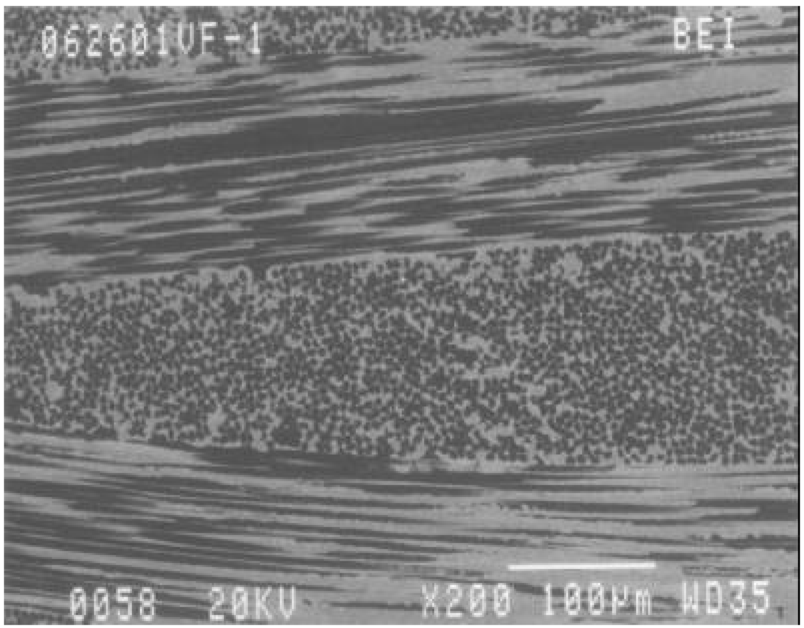
Front

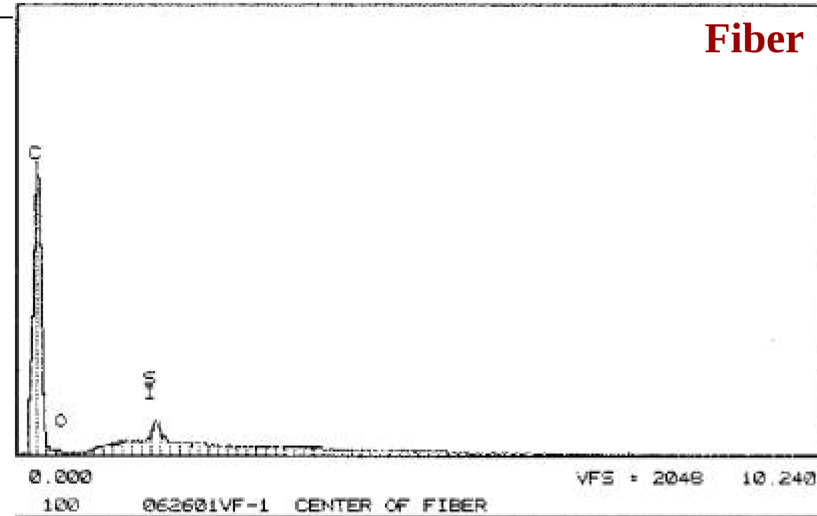
Back

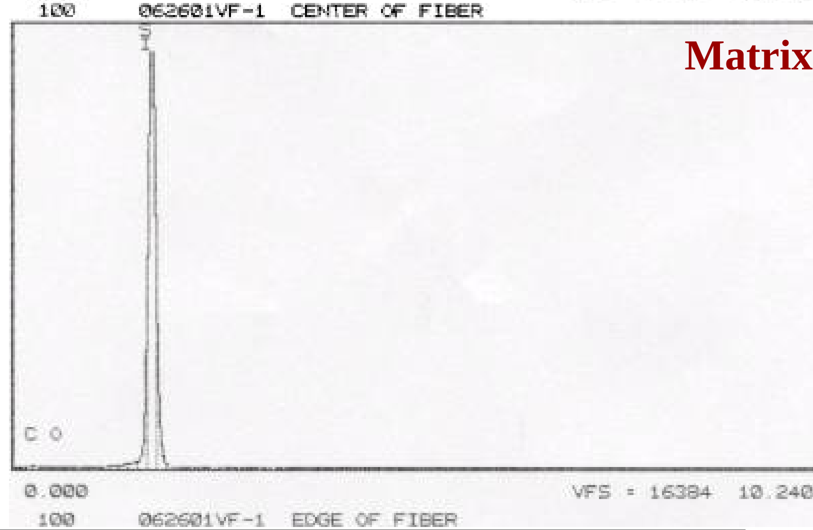
Light-weight (~15kg/m^2), 12 inch diameter substrate made of M Cubed Si/SiC (SSC)

M Cubed Technologies: Production Equipment

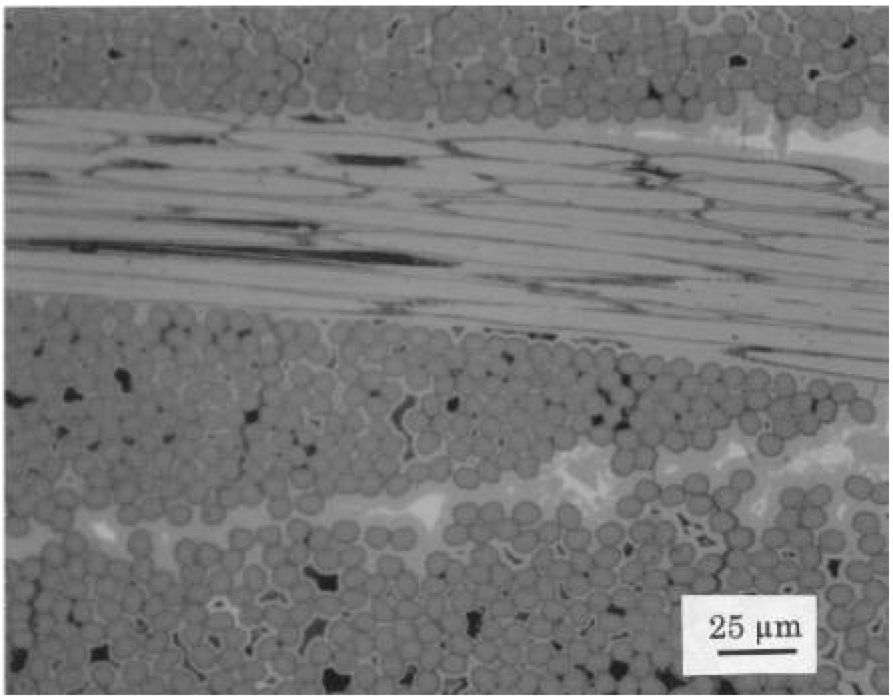
Microstructure of C_f/SiC Composite 1

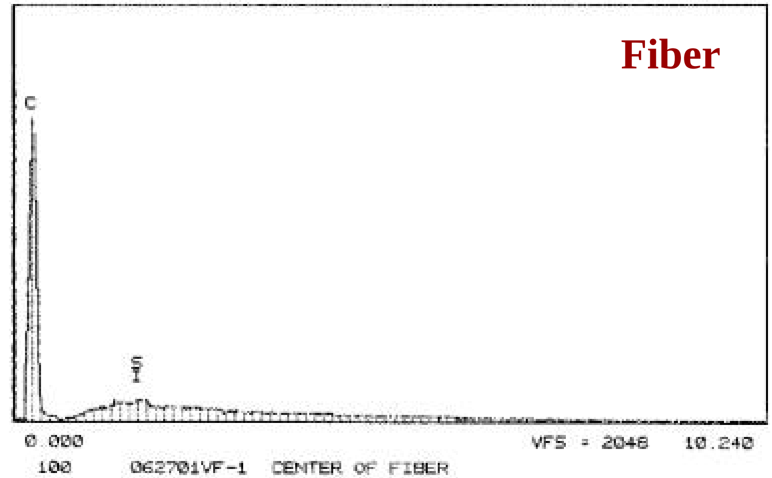


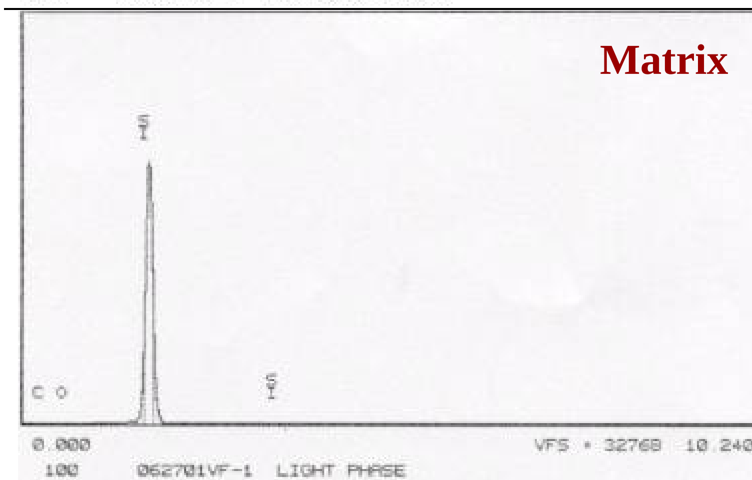




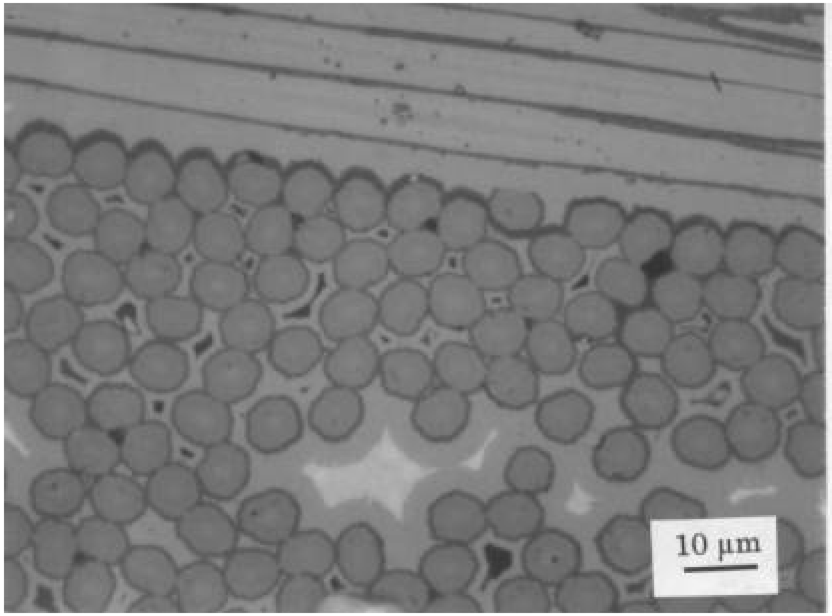
Microstructure of C_f/SiC Composite 2



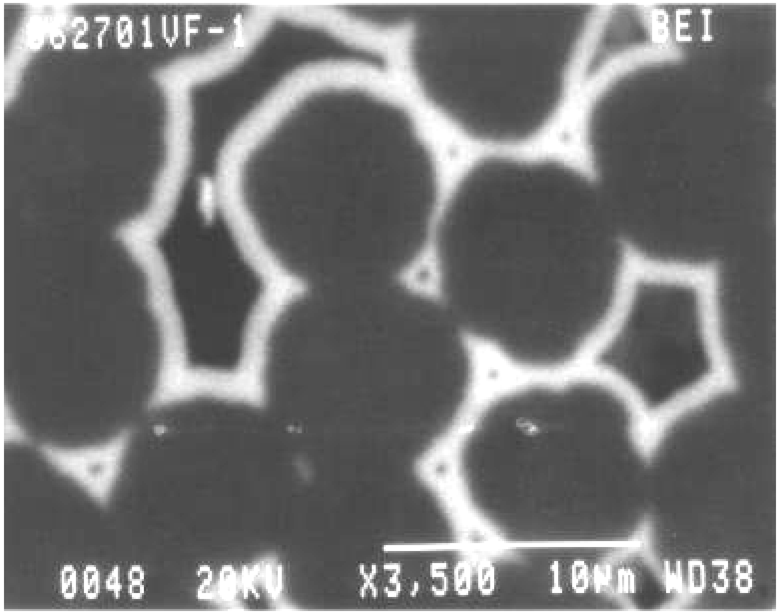




Microstructure of C_f/SiC Composite 2



Optical Micrograph



Back Scattered Electron Image

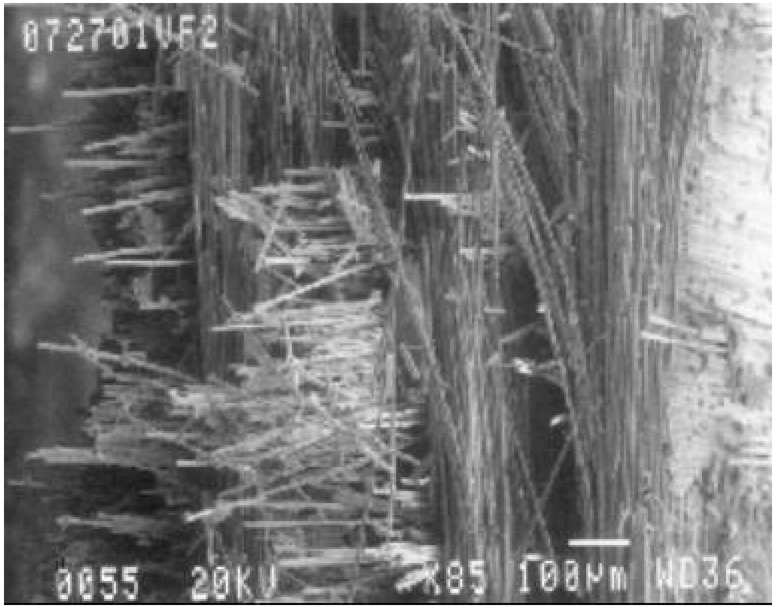
C_f/SiC: Measured Properties (prior to Phase I start)

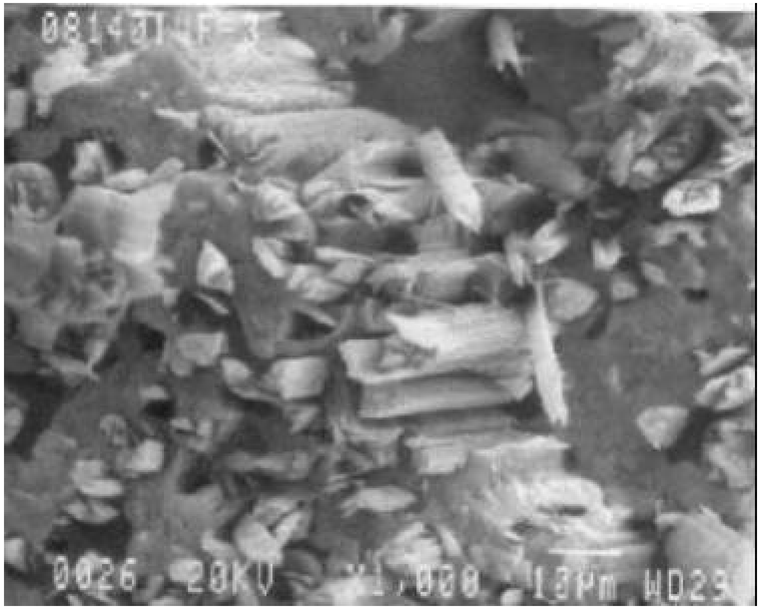
Composite	Density (g/cc)	Flexural Strength (MPa)	UTS (MPa)	Young's Modulus E (GPa)	CTE (-50 to 100°C) ppm/K	Thermal Cond. W/mK
1	2.394	64.5	32.9	154.5	0.96	68.3
2	1.995	156.0	85.5	61.3	0.77	15.5
3	2.448	108.5	--	--	1.06	91
4	2.568	183.5	--	--	1.75	143
5	2.348	126.2	--	--	1.84	94
6	2.490	162.1	107.7	112.0	-0.46	x: 114 y: 122
Invar	8.0	--	455	150	1.8	13
Zerodur	2.57	55-90	--	90	0	1.6

8HS: 8 harness satin weave; PW: plain weave; Q-Iso: quasi isotropic laminate [0/90/+45/-45]s

- **Mechanical properties were significantly enhanced during the Phase I but were not cleared in-time for public presentation.**

Fracture Surfaces of C_f/SiC Composites

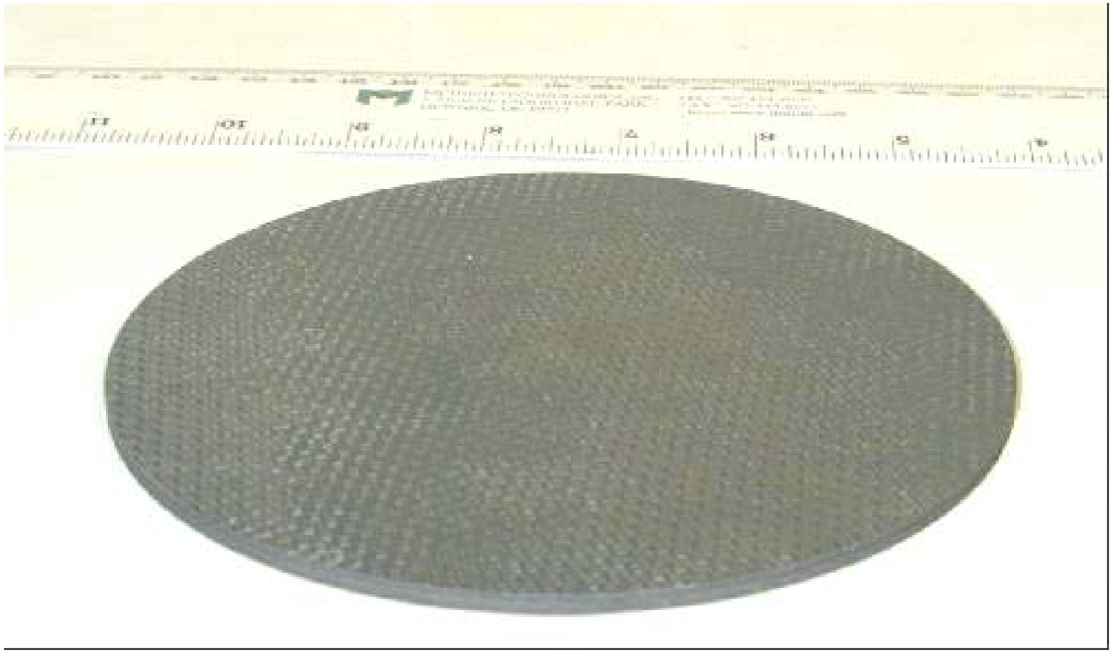




- Fiber pullout is obtained in the composite indicating non-catastrophic failure

C_f/SiC Substrate for a Mirror

6” diameter C_f/SiC mirror substrate (made prior to Phase I)



- **In the Phase I**
  - **8 inch ribbed-back, light-weighted substrate has been made, and finished**
  - **20 inch spherical mirror substrates has been made**

Phase I Achievements

- **In the Phase I Program, the C_f/SiC composite mechanical properties were significantly enhanced (results were not cleared in-time for public presentation)**
- **An 8-inch and 20-inch specimens were fabricated with down-selected material**
- **Phase I demonstrated feasibility and met all the technical objectives**
- **Manufacturing capability exists to manufacture up to 1.5 m diameter mirrors in production volumes**